SPACE-TIME AND SPACE-FREQUENCY HOPPING FOR CAPACITY ENHANCEMENT OF MOBILE DATA SYSTEMS

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RELATED APPLICATIONS

The present application is related to co-pending United States provisional patent application serial number 60/190,009 entitled "Space-Time and Space-Frequency Hopping for Capacity Enhancement of Mobile Data Systems," filed March 17, 2000, to which the benefit of priority of filing is hereby claimed and the disclosure of which is hereby incorporated herein by reference.

The present application is also related to co-pending and commonly assigned United States patent application serial number 09/229,482, entitled "Practical Space-Time Radio Method for CDMA Communication Capacity Enhancement", filed on January 13, 1999,

United States patent application serial number 09/511,665 entitled "Transmitting Beam Forming In Smart Antenna Array Systems", filed February 23, 2000, United States patent application serial number 09/310,567 entitled "Manifold Assisted Channel Estimation and Demodulation for CDMA Systems in Fast Fading Environments", filed May 12, 1999, and United States patent application serial number 09/450,318 entitled "Polarization and Angular Diversity Among Antenna Beams", filed November 29, 1999, the disclosures of which are hereby incorporated herein by reference.

TECHNICAL FIELD

The present invention relates generally to mobile data systems and, in particular, to increasing subscriber capacity through use of time, frequency, and/or space hopping techniques.

BACKGROUND

The wireless telecommunications market has experienced an enormous subscriber growth in recent years, with no signs of slowing. It is therefore becoming more and more essential for wireless network operators to be able to increase capacity (i.e. support more subscribers) with the limited available spectrum of transmission frequencies.

5   There are currently a number of techniques in use or under development to improve the downlink (base-station-to-mobile subscriber) transmission capacity of wireless networks. The most common technique is to use sectored antennas within cells whereby either separate antennas or separate beams of a phased array antenna system are used to cover different geographic sectors within the cell. Other techniques for increasing network capacity include

10   time division multiple access ("TDMA") and frequency division multiple access ("FDMA") such as used by, for example, the GSM ("Global System for Mobile telecommunications") system predominant in Europe. Code division multiple access ("CDMA") is an increasingly pervasive technique for expanding subscriber capacity.

Most typically, cells are divided into three or six sectors, where each sector covers 120° or 60° degrees respectively. With this approach, the capacity of a cell with three equal-

15   sectored (120°) antennas, for example, is increased due to an increase in the reuse of channels throughout the network and/or improved signal quality associated with the use of directional antennas. For example, in a code division multiple access system, theoretically three times the capacity of that of a cell using an omnidirectional antenna at the base station may be

20   achieved using a three sectored system. Ideally, the capacity could be improved *n*-fold by employing *n* 2p/*n* radian beamwidth antennas or antenna sectors. As a practical matter, this ideal increase is not possible due to the necessity and desirability of some beam overlap (see, Viterbi, CDMA, Principles of Spread Spectrum Communications, p. 227 (1995) incorporated herein by reference).

25   Yet another approach to increased wireless system capacity is the use of multiple beam, or "smart" antennas, such as shown and described in the above referenced patent application entitled "Polarization and Angular Diversity Among Antenna Beams." Systems

utilizing smart antenna systems have the ability to form or select relatively narrow beams for transmission depending upon a subscriber's position relative to the base station, rather than transmitting on a single beam encompassing the antenna's entire coverage area. The use of such multiple beam antennas provides for selection of relatively narrow antenna beams for providing communications with respect to a particular mobile unit. Accordingly, the amount of interfering energy experienced in the communicated signals is reduced because power is not wasted by having it transmitted to areas where it cannot be received by the subscriber.

Such smart antenna systems may be used in combination with standard frequency hopping techniques (see, for example, Kronestedt and Andersson, "Adaptive Antennas in Frequency Hopping GSM", ICUPU 1998, pp. 325-29 incorporated herein by reference). Frequency hopping consists of altering the carrier frequency transmitted to a given subscriber between transmission time frames.

However, it should be appreciated that in the previously proposed schemes, the antennas are not truly adaptive. Adaptive antennas can be controlled to transmit relatively narrow, focused beams directed at an individual subscriber, where the beam width is chosen to be as small as possible to provide the desired or necessary power to the subscriber through the use of complex antenna signal weighting. Instead of providing such adaptive antenna configurations, the previously proposed schemes transmit on a series of fixed beams, such as may be associated with a fixed beam forming network, e.g., a Butler matrix.

Accordingly, a need exists in the art for systems and methods which provide increased subscriber capacity in a wireless communication system over that available through the use of currently available techniques, such as sectorization, switched beam smart antenna systems, and frequency hopping.

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SUMMARY OF THE INVENTION

The present invention is directed to a system and method in which the use of narrow antenna beams is combined with techniques implemented to pseudo randomize occurrences of interference to reduce or average the effects of such interference and, thereby, provide subscriber capacity increases. Accordingly, embodiments of the present invention may utilize frequency (e.g. carrier frequency) hopping, time (e.g. time slot or burst period) hopping, and/or space (e.g. directional antenna beam) hopping.

Preferably, adaptive beam forming techniques are utilized in providing narrow antenna beams used according to the present invention to minimize radio frequency within the service area. It should be appreciated that the use of a true adaptive antenna, i.e., one capable of dynamic forward beam forming directed to a particular subscriber, is a challenge to implement in a mobile wireless communication system. For example, because of differences in the forward and reverse link channels and/or due to the use of carrier frequencies having different propagation characteristics in the forward and reverse link channels, it is generally difficult to determine signal weighting parameters to form an adaptive antenna beam in one such link channel based upon channel characteristics of the other such link channel. However, systems and methods for determining mobile subscriber unit location and for the formation of adaptive antenna beams have recently been developed, as are shown and described in the above referenced applications entitled "Transmitting Beam Forming In Smart Antenna Array Systems" and "Manifold Assisted Channel Estimation and Demodulation for CDMA Systems in Fast Fading Environments".

A preferred embodiment of the present invention combines the use of true adaptive antennas, to provide highly directional forward link antenna beams, with time slot hopping to improve wireless network capacity. According to this embodiment of the invention, multiple subscriber units may be provided communications during a communication frame or set of frames (e.g. a "super frame"), each in an assigned time slot of the frame, by directing an antenna beam thereto during the respective time slot (referred to herein as space-time hopping). In successive frames the time slot assigned to a particular subscriber unit is

changed, i.e., hops, to a different frame time slot. The time slot hops according to the present invention may be sequential, e.g. selecting a next or previous frame time slot, or pseudo random, e.g. selecting a time slot in no apparent order. Through use of different time slots for a subscriber unit's communications, interference associated with the use of any one particular time slot, such as may result from a subscriber unit operating in a neighboring service area using a corresponding time slot, may be avoided or otherwise mitigated.

Preferred embodiments of the present invention may use frequency hopping in combination with time slot hopping in the technique described above. Accordingly, an additional degree of freedom is provided for use in avoiding or otherwise mitigating interference. According to this embodiment of the invention, multiple subscriber units may be provided communications during a communication frame or set of frames (e.g. a "super frame"), each in an assigned time slot of the frame using an assigned carrier frequency, by directing an antenna beam thereto during the respective time slot (referred to herein as space-time-frequency hopping). Preferably, in successive frames the time slot assigned to a particular subscriber unit hops to a different frame time slot and the carrier frequency assigned to a particular subscriber unit is changed, i.e., hops, to a different carrier frequency. As with the time slot hops described above, the frequency hops according to the present invention may be sequential, e.g. selecting a next or previous carrier frequency, or pseudo random, e.g. selecting a carrier frequency in no apparent order.

Space-time, space-frequency and space-time-frequency hopping according to the present invention give rise to a time-varying interference power received by a subscriber. The time-varying interference power provides a diversity gain with respect to a system which may be realized according to the present invention using conventional interleaving, error control coding and adaptive modulation techniques.

It should be appreciated that time slot and frequency hopping according to the present invention need not be carried out according to a same algorithm. For example, time slot hopping may be sequential while frequency hopping is pseudo random. Likewise, time slot

hopping may be carried out with one period, such as on a single frame bases, while frequency hopping is carried out with another period, such as on a super frame basis.

There is no limitation that such hopping techniques be utilized throughout communications according to the present invention. For example, a particular hopping technique may be implemented upon the occurrence of a condition, such as when a communication system reaches a particular capacity, when communication quality reaches a particular threshold, or even after one particular hopping technique has been implemented and desired results have not been fully achieved.

According to a preferred embodiment of the present invention multiple antenna beams may be utilized, such as in the forward link, to provide simultaneous communications to a plurality of subscriber units. In situations where sufficient isolation is proved for the communication of signals associated with multiple subscriber units, such as where such units have sufficient spatial separation, the present invention may serve multiple groupings of subscriber units, preferably using the above described time and/or frequency hopping techniques to provide interference diversity gain allowing simultaneous communications, to further increase subscriber capacity. For example, two or more simultaneous forward link beams are formed and redirected during particular time slots to respective subscriber units separated sufficiently in angle. For each transmission frame, the time slot and/or carrier frequency for each subscriber unit is varied such that the beam switching, or hopping, sequence is pseudo random.

Two preferred embodiment algorithms are described herein to provide forward link beam forming according to the present invention. These two preferred embodiment algorithms are a fast hopping algorithm and a slow hopping algorithm.

According to a preferred embodiment fast hopping algorithm, the hopping rate is greater than the interleaving frame rate, preferably on the order of several times the interleaving frame rate. Preferably, using conventional adaptive modulation or adaptation of the processing gain, the data rate available to a subscriber unit is based upon the carrier-to-interference ratio (C/I) of a pilot signal (which illuminates an entire sector), the gain of the

antenna array and the interference diversity gain. Diversity gain is estimated from the statistics of the interference environment. Estimates of the diversity gain are adapted slowly as the interference environment changes. Accordingly, although a particular subscriber unit may experience interference sufficient to result in a higher than acceptable error rate, this

5   interference will be experienced for a sufficiently short duration (because of the fast hopping) that the subscriber unit is provided with acceptable communications. For example, where the hopping rate is selected to be sufficiently short, the above described period of an unacceptable error rate may result in loss of a few symbols which may be corrected by forward error correction (FEC) techniques well known in the art.

10   According to a preferred embodiment slow hopping algorithm, the hopping rate is less than the interleaving frame rate, preferably on the order of a tenth or tenths of the interleaving frame rate. During each hop the active subscribers preferably adapt the data rate according to measured channel characteristics, such as the C/I measured on the traffic channel according to conventional techniques. According to a preferred embodiment, the slow hopping algorithm

15   uses not only pilot C/I measurement, but also an estimated channel quality indicator from a traffic channel. Preferably, in order to maintain a constant data rate for the duration of each hop, hopping at neighboring base stations is time synchronized in order that the measured channel characteristics remain substantially constant throughout a hop. Slow hopping is applicable for long burst communications where sufficient time is available for measuring the

20   channel characteristics.

            A technical advantage is provided in that utilizing hopping techniques of the present invention, systems utilizing communications standards such as Global System for Mobile Communications (GSM), Interim Standard 136 (IS-136), General Packet Radio Service (GPRS), Enhanced Data Rates for GSM Evolution (EDGE), and Qualcomm's High Data

25   Rate (HDR) may be provided increase interference diversity gain and, therefore, increased subscriber capacity and/or improved signal quality. For example, an HDR system may be adapted according to the present invention to include adaptive antennas capable of transmitting simultaneous beams, together with time slot hopping to provide increased

interference diversity gain. However, because downlink transmission occupies the entire available downlink bandwidth, it may not be desirable to implement frequency hopping according to the present invention to thereby avoid significant adaptation of the HDR system. A GSM system, on the other hand, may readily be adapted according to the present invention

5   to utilize adaptive antennas, frequency hopping, and time hopping to improve network capacity

The foregoing has outlined rather broadly the features and technical advantages of the present invention in order that the detailed description of the invention that follows may be better understood. Additional features and advantages of the invention will be described

10 hereinafter which form the subject of the claims of the invention. It should be appreciated by those skilled in the art that the conception and specific embodiment disclosed may be readily utilized as a basis for modifying or designing other structures for carrying out the same purposes of the present invention. It should also be realized by those skilled in the art that such equivalent constructions do not depart from the spirit and scope of the invention as set

15 forth in the appended claims. The novel features which are believed to be characteristic of the invention, both as to its organization and method of operation, together with further objects and advantages will be better understood from the following description when considered in connection with the accompanying figures. It is to be expressly understood, however, that each of the figures is provided for the purpose of illustration and description

20 only and is not intended as a definition of the limits of the present invention.

BRIEF DESCRIPTION OF THE DRAWING

For a more complete understanding of the present invention, reference is now made to the following descriptions taken in conjunction with the accompanying drawing, in which:

FIGURE 1A illustrates the concept of time slot hopping;

FIGURE 1B illustrates the concept of frequency hopping;

FIGURE 2 illustrates the components of a conventional network base station;

FIGURE 3 illustrates the components of an adaptive array enhanced base station in accordance with one embodiment of the present invention;

FIGURE 4 is a graph showing interference diversity gain averaged over subscriber positions within a cell;

FIGURE 5 is a flow chart of a fast hopping algorithm according to one embodiment of the present invention;

FIGURE 6 is a flow chart of a slow hopping algorithm according to one embodiment of the present invention; and

FIGURE 7 is a graph showing the coded bit error rate performance of fast hopping and no beam forming for a single interferer.

DETAILED DESCRIPTION

FIGURES 1A and 1B illustrate the concepts of frequency hopping and time slot hopping for two subscribers (S1 and S2) using a deterministic hopping sequence. In the examples of FIGURES 1A and 1B, there are eight time slots per frame (T1, T2, ..., T8), similar to a conventional TDMA scheme. The carrier frequency (f1, f2, ..., fN) is shown to the left of each frame. Although particular embodiments are illustrated, it should be appreciated that the present invention is not limited to such embodiments. For example, more or less than the illustrated time slots per frame may be utilized. Additionally, hopping may be implemented on a "super frame" bases rather than frame by frame as illustrated. Similarly, there is no requirement that a same carrier frequency be utilized throughout a particular frame.

In the time slot hopping of FIGURE 1A, the carrier frequency remains constant while the position within a frame of the time slot for each subscriber (S1 and S2) varies between frames. In the frequency hopping of FIGURE 1B, the position within a frame of the time slot for each subscriber (S1 and S2) remains constant while the carrier frequency varies between frames. Although a deterministic hopping sequence is shown in FIGURES 1A and 1B, a pseudo random sequence is preferably chosen in practice.

As further discussed below, either or both technique may be used with narrow directional antenna beams according to the present invention to provide communications with multiple subscriber units having increased interference diversity gain. When combined with the use of narrow antenna beams directed to a particular subscriber unit as described herein ("space hopping"), a generalization of time slot and frequency hopping can be referred to as "space-time-frequency hopping" in which both the time slot and carrier frequency for each subscriber are varied. According to the preferred embodiment, the particular antenna beam used for data transmission will vary between subscribers according to their position relative to the base station. In this way, system capacity can be increased substantially because interference is avoided or otherwise mitigated as data communication for each subscriber unit is conducted during various time slots and/or on various carrier frequencies.

        Preferred embodiments of the present invention utilize adaptive array antennas to

provide the aforementioned narrow beams adapted for channel conditions associated with the

subscriber units. Adaptive array antennas suitable for use according to the present invention

are shown and described in the above referenced patent application entitled "Transmitting

5   Beam Forming in Smart Antenna Array Systems". However, alternative embodiments of the

present invention may utilize switched narrow beam systems, such as shown and described in

the above referenced patent application entitled "Polarization and Angular Diversity Among

Antenna Beams".

        FIGURE 2 illustrates in simplified fashion the operation of a standard wireless

10   network communications base station 200 in accordance with the prior art. Data for

transmission 210 is processed through a baseband modem 220, an IF (intermediate

frequency) transceiver 230, an RF front-end transceiver 240, and transmitted through antenna

250 as data packet 260. In the illustrated embodiment, antenna 250 comprises a single

element, meaning an omni directional or wide fixed beam is used for each transmission. The

15   process is reversed for the receipt of data at the base station from the subscriber.

        FIGURE 3 illustrates in simplified form the operation of a wireless network

communications base station 300 in accordance with one embodiment of the present

invention. Data element 310 is processed for transmission through a baseband modem 320

and then sent to a beam-forming machine 340. Note that while only a single data element

20   310 is illustrated, it may be comprised of multiple individual data packets for transmission to

different users.

        Preferably using one of the beam forming algorithms more fully disclosed herein,

beam-forming machine 340 determines the proper weights (e.g. signal amplitude, signal

phase, and/or in-phase and quadrature (IQ) relationships) for signals carrying data element

25   310 to IF transceiver elements 350a-350n in the transmitting array. Specifically, based upon

the position of the particular subscriber unit (not illustrated) data element 310, or a portion

thereof, is to be transmitted, beam-forming machine 340 provides proper weighting of signals

passed there through to result in free-space combining of the signals for optimized

communication with the desired subscriber unit. Accordingly, it should be appreciated that more than one transceiver is likely to be provided with a weighted signal carrying data element 310 in order that a relatively narrow directional antenna beam may be formed. Moreover, preferred embodiments of the present invention provide for simultaneous

5   transmission of data to multiple subscriber units through simultaneously forming multiple beams. Accordingly, more than one transceiver is likely to be provided a signal for transmission in such an embodiment.

The output signals of IF transceivers 350a-350n of the illustrated embodiment are passed to its corresponding RF front-end transceivers 360a-360n and then to antenna

10   elements 370a-370n. Antenna elements 370a-370n may be any form of radio frequency active element, such as a dipole, micro-strip patch, heliacal coil, or like antenna element well known in the art. Signals radiated from antenna elements 370a-370n preferably combine in free space to illuminate locations associated with subscriber units with a corresponding one of data packets 380a-380n.

15   It should be appreciated that antenna elements 370a-370n of the preferred embodiment comprise a phased array antenna and, therefore, are preferably disposed in a predetermined geometry. Although shown as individual antenna elements, it should be appreciated that one or more of antenna elements 370a-370n may actually include multiple antenna elements, such as a column of radiating elements. It should also be appreciated that

20   any number of antenna elements (or antenna element columns) may be utilized according to the present invention, but between 6 and 21 are considered most optimal.

The base station receiving process (reverse link) is largely the reverse of the transmission process (forward link) described above. Data packets 380a and 380b from subscriber units are received by antenna elements, which may be antenna elements 370a-370n

25   used in transmission or different antenna elements (not shown). The signals received by the antenna elements are preferably processed by corresponding RF front-end transceivers, such as RF front-end transceivers 360a-360n, IF transceivers, such as IF transceivers 350a-350n, a beam former, such as beam forming machine 340, and a signal processor, such as baseband

modem 320. The beam-forming machine is used for reverse link beam forming. The received data is also preferably routed through subscriber unit direction finding circuitry, such as direction finding machine 390, which is used to determine the subscriber's location for the selection of the most appropriate antenna beam or signal weighting scheme for

5   subsequent communication. A more complete description of transmitting and receiving antenna arrays and associated circuitry may be found in the above referenced patent application entitled "Transmitting Beam Forming in Smart Antenna Array Systems".

It should be appreciated that the circuitry of base station 300 may operate under the control of a control algorithm (not shown) such as may be operable on a processor based

10   system. For example, a general purpose processor based system, such as may be based upon the INTEL PENTIUM processor platform, may provide control of direction finding, beam forming, and/or other aspects of the present invention. Accordingly, such control algorithms may be operable within beam forming machine 340, direction finding machine 390, and/or a separate controller (not shown).

15   Multiple techniques may be utilized according to the present invention to provide interference diversity gain. As previously mentioned hopping of one or more communication attributes, including space, time, and/or frequency, may be applied in communication sessions conducted according to the present invention. Moreover, hopping of communication attributes according to the present invention may be provided in various ways. For example,

20   a preferred embodiment of the present invention utilizes a fast hopping technique. Another embodiment of the present invention utilizes a slow hopping technique.

Fast Hopping Embodiment

In one embodiment of the present invention, hopping of various communication attributes is provided at a rate faster than the interleaving frame rate (referred to herein as the

25   fast hopping system or fast hopping algorithm). According to this embodiment, a channel estimation is preferably made for each subscriber. For example, the C/I (carrier to

interference ratio) of each subscriber may be estimated as the sum (in dB) of the C/I of the pilot channel, the antenna array gain and the interference diversity gain. The direction of each subscriber unit is assumed to be known with reasonable accuracy, such as to within 5° as shown in the above referenced patent application entitled "Practical Space-Time Radio Method for CDMA Communication Capacity Enhancement". The interference diversity gain may be estimated as illustrated in FIGURE 4 using an effective beam width greater than the minimum beam width since simultaneous hopping beams may be used.

Simultaneous hopping beams may be used as necessary according to the present invention to operate in a power efficient region, defined as a region of C/I in which the ratio of data rate to required C/I is above a threshold. In the HDR system, for example, the power efficient region (i.e., $C/I <= C/I_{sat}$, where $C/I_{sat} = 3.0$ dB for the HDR system) corresponds to quadrature phase shift keying (QPSK) modulation and adaptation of the processing gain. When $C/I > C/I_{sat}$, higher order constellations are used, resulting in a reduction of the ratio of data rate to required C/I.

A flow chart of a preferred embodiment fast hopping algorithm, as applied to the HDR system with 120-degree sectors, is shown in FIGURES 5A and 5B. Those skilled in the art will appreciate that the described method can be readily adapted to other TDMA based systems as well. A detailed description of such an embodiment of the fast hopping algorithm is given below.

As shown in FIGURE 5A, the fast hopping algorithm of the illustrated embodiment is initialized by setting a parameter N_{sel} to zero in step 510. For each hop interval, any new packets (along with the corresponding time of packet arrivals, not shown) are placed on the queue for transmission in step 512. The queue times for all packets are then preferably computed (not shown) and the number of subscribers with packet queue time greater than or equal to an established threshold time T_{max} determined in step 514.

If there are any subscribers with packet queue times greater than or equal to T_{max} (step 514), a set of N_{max} candidate subscribers with the best pilot C/I ratios is preferably selected among the subscribers with packet queue times greater than T_{max} in step 516 and processing

proceeds to step 524. N_{max} is preferably determined by system design parameters. For example, according to a preferred embodiment N_{max} is determined principally as a tradeoff between computational complexity if N_{max} is too large, and a low probability of simultaneous beam formation if it is too small. As shown in Table 1, 8 is considered to be a typical number for N_{max}.

If all packet queue times are less than T_{max}, (step 514) and one of three conditions are satisfied, a set of N_{max} candidate subscribers with the best pilot C/I ratio is preferably selected among the subscribers with packets in the queue in step 520 and processing proceeds to step 524. The three conditions are $N_{sel} = 0$ (step 518), not all N_{sel} subscribers in the selected combination have data in the queue (step 519), or the selected combination was determined T_{sel} ago (step 522).

At step 524 the subscriber with the highest pilot C/I ratio among the N_{max} candidate subscriber units is preferably identified. Thereafter, according to the illustrated embodiment of the present invention, the sum (in dB) of the pilot C/I, interference diversity gain and antenna array gain is calculated for this subscriber in step 524 and, if greater than C/I_{sat}, the parameters N_{sel} (the subscriber units selected for simultaneous service in the current hop interval) and θ_{min} (the angular separation of the simultaneously active subscriber units) are set in step 526, otherwise N_{sel} and θ_{min} are set in step 528. At step 526, N_{sel} and θ_{min} are preferably set as follows: $N_{sel} = 120/B$ (it being appreciated that 120 is the sector width of the HDR system of the illustrated embodiment), $\theta_{min} = B$, where $B > 0$ (B representing the minimum beam width in degrees according to this embodiment). At step 528, N_{sel} and θ_{min} are preferably set as follows: $N_{sel} = 120/\theta$, $\theta_{min} = \theta$, step 528, where $0 < \theta < B$ (θ representing the minimum angular separation of active subscribers).

It should be appreciated that values for B and θ may be selected with consideration of a number of parameters. For example, the minimum beam width B may be selected as the most narrow beam width which may be formed by the antenna array utilized or, more preferably, may be selected to be a minimum beam width for providing acceptable communications, such as may be affected by propagation conditions, scattering, frequencies

utilized, and other network conditions. The value of θ may be selected by such

considerations as a minimum angular spread of subscriber units providing a desired level of

isolation for communication of signals associated therewith. For example, θ may be selected

as a function of the minimum beamwidth B selected, such as approximately ½ B to ensure

5   that the subscriber units are disposed a sufficient angle off of bore sight of an antenna beam

used in communication with another such subscriber unit.

Once N_{sel} and θ_{min} are determined, all combinations of the N_{max} candidate subscribers

taken N_{sel} at a time are preferably considered in step 530 to determine valid combinations of

subscribers which may be served in the current hop interval according to this embodiment of

10   the invention. For example, combinations which correspond to a minimum angular

separation among subscribers of less than θ_{min} are discarded as invalid combinations (not

shown). At step 532 it is determined if any valid combinations of N_{max} candidate subscribers

are identified by the considerations in step 530. If no valid combination of N_{max} candidate

subscribers is identified, processing preferably proceeds to step 534 where N_{sel} is preferably

15   decremented, and the search for valid combinations is repeated in step 530 with the new value

of N_{sel}. The process of decrementing N_{sel} by one and searching for a valid combination

preferably continues until either $N_{sel} = 1$ or a valid combination is found.

At step 532, if a valid combination of N_{max} candidate subscribers is identified

($COMB_{sel}$) or $N_{max}=1$, processing preferably proceeds to step 536 (FIGURE 5B) where the

20   subscribers to be served in the current hop interval are decided. If $\theta_{min} \neq B$ (step 536)

processing proceeds to step 538 for identification of the particular subscriber units to be

served in the current hop interval. Alternatively, if $\theta_{min} = B$ (step 536) processing proceeds to

step 540 for identification of the particular subscriber units to be served in the current hop

interval.

25   At step 538 the subscriber with the highest pilot C/I among the subscribers in

$COMB_{sel}$ is preferably chosen for service in the current hop interval, the number of

subscribers to be served in the current hop interval, N_{sub}, is preferably set to one, and

processing proceeds to step 542. The remaining subscribers in $COMB_{sel}$ ($N_{rem} = N_{sel} - 1$) are

preferably served in subsequent hop intervals according to this embodiment of the invention.

At step 540 the transmit power associated with the subscriber with the highest pilot C/I (among the subscribers in $COMB_{sel}$) is preferably reduced such that the sum (in dB) of the pilot C/I, antenna array gain and interference diversity gain is equal to C/I_{sat}. Remaining transmit power is preferably used according to this embodiment to form a simultaneous hopping beam for the subscriber with the best channel (highest pilot C/I) among the remaining $N_{sel} - 1$ subscribers in $COMB_{sel}$. Additional simultaneous beams are preferably formed in a similar manner until, for all N_{sub} subscribers to be served simultaneously, the sum (in dB) of the pilot C/I, antenna array gain and interference diversity gain is less than or equal to C/I_{sat}. The remaining $N_{rem} = N_{sel} - N_{sub}$ subscribers in $COMB_{sel}$ are preferably served in subsequent hop intervals.

At step 542 data rates for the subscriber units to be served in the current hop interval are preferably selected. For example, for each subscriber $k=1,2,\ldots, N_{sub}$ to be served simultaneously in the current hop interval, the sum (in dB) of the pilot C/I, antenna array gain and interference diversity gain may be used to select an appropriate data rate from a table or matrix of required C/I ratios and corresponding data rates for the HDR system of the illustrated embodiment. It should be appreciated that Qualcomm provides such data rate information for use with its HDR systems. However, such data rate information may be determined theoretically (e.g. using simulations) or empirically through reference to such parameters as the modulation scheme, the coding scheme, the interleaver period, the target bit and/or frame error rate.

Steps 544-557 identify the subscriber units of the N_{sub} subscriber units for which the identified data rate is greater than zero (or possibly some other threshold data rate value) and provides data transmission thereto using hopping techniques as described herein. Specifically, at step 544 it is determined if the subscriber unit under consideration (k) is <= N_{sub} and, if so, processing proceeds to step 548. At step 548 it is determined if the data rate for the subscriber unit under consideration is greater than zero and, if so, processing proceeds to step 557 for adding the subscriber unit under consideration to an active list of subscriber

units for transmission in the current hop interval and incrementing k to the next subscriber unit of N_{sub}. If, however, the data rate for the data rate for the subscriber unit under consideration is zero at step 548, processing proceeds to step 552 where it is determined if the data rate has been zero for this subscriber unit for a consecutive number of times greater than N_{drop}. If the data rate for this subscriber unit has been zero for N_{drop} consecutive times, the subscriber unit is preferably dropped from the system and k is incremented to the next subscriber unit of N_{sub} at step 554. If, however, the data rate for this subscriber unit has not been zero for N_{drop} consecutive times, k is incremented to the next subscriber unit of N_{sub} at step 556. When, at step 544, it is determined that the subscriber unit under consideration (k) is no longer $<= N_{sub}$, transmission to all subscriber units placed on the active list of subscribers for transmission in the current hop interval is provided using hopping techniques as described herein (step 546).

Preferably, in the next hop interval, a new set of N_{max} candidate subscribers is selected as described above if any of the three following conditions is satisfied: (a) there are subscribers with packet queue times greater than or equal to T_{max}, step 514, or (b) the previous combination, $COMB_{sel}$, was selected less than a threshold time T_{sel} ago, step 522, or (3) not all N_{sel} subscribers of $COMB_{sel}$ have data present in the transmit queue, step 518. If none of conditions (a), (b), or (c) is satisfied, the combination, $COMB_{sel}$, of subscribers is used in the next hop interval in step 542.

Although not specifically shown in the embodiment illustrated in FIGURES 5A and 5B, the set of N_{rem} subscribers not served in the current hop interval is preferably given higher priority for transmission in subsequent hop intervals than the set of N_{sub} subscribers served in the current hop interval. Within the set of N_{rem} subscribers, priority is preferably assigned in order of decreasing pilot C/I. Similarly, within the set of N_{sub} subscribers, priority is preferably assigned in order of decreasing pilot C/I. The N_{sel} subscribers of $COMB_{sel}$ are preferably served in order of decreasing priority in subsequent hop intervals until either condition (a) or (b) is satisfied. If the lowest priority subscriber is served before either condition (a) or (b) is satisfied, the sequence of transmissions preferably repeats starting with

the highest priority subscriber.

Typical parameters for use according to the preferred embodiment fast hopping algorithm are given in Table 1:

Table 1: Typical System Parameters

Path Loss Exponent (n)	3
Standard Deviation of Lognormal Shadowing (σ)	8 dB
Minimum Beam Width (B)	30°
Minimum Angular Separation (θ)	20°
C/I Threshold for Forming Simultaneous Beams (C/I_{sat})	3.0 dB
Number of Candidate Subscribers (N_{max})	8
Queue Time Threshold (T_{max})	0.5 sec
Maximum Time for a Given Selected Combination (T_{sel})	1 sec
Drop Threshold (N_{drop})	10

Slow Hopping Embodiment

In a second embodiment of the present invention, hopping of various communication attributes is provided at a rate slower than the interleaving frame rate (referred to herein as the slow hopping system or slow hopping algorithm). According to a preferred embodiment slow hopping system, the number of simultaneous beams is chosen as large as possible to maximize the aggregate throughput during each hop interval. The criterion used to select the simultaneous beams is preferably maximization of the sum (in dB) of the pilot channel C/I ratios of the active subscribers in each time slot. As with the fast hopping system discussed above, the direction of each subscriber is assumed to be known to with reasonable accuracy, such as to within 5°. The minimum angular separation of the active subscribers (θ_{min}) for this embodiment is preferably equal to the minimum beam width (B). Once the active subscribers are selected, the data rate for each subscriber is preferably selected using the C/I measured on the traffic channel. A flow chart of a preferred embodiment slow hopping algorithm of the present invention, as applied to an HDR system with 120-degree sectors, is shown in FIGURES 6A and 6B. Once again, those skilled in the art will appreciate that the slow hopping methods described below can be adapted to other TDMA based systems as well.

The slow hopping algorithm of the illustrated embodiment is preferably initialized by setting a parameter N_{sel} to zero in step 610. At step 612, for each hop interval, any new packets (along with the corresponding time of packet arrivals) are preferably placed on the queue for transmission and the queue times for the packets computed. At step 614 a determination is made as to whether there are any subscribers with packet queue times greater than or equal to a threshold T_{max}. If there are subscribers with packet queue times greater than or equal to T_{max} then processing preferably proceeds to step 616 wherein a set of N_{max} candidate subscribers with the best pilot C/I ratio is selected among the subscribers with packet queue times greater than T_{max}. However, if all packet queue times are less than T_{max} in step 614, and one of the following three conditions are satisfied, a set of N_{max} candidate subscribers with the best pilot C/I ratios is preferably selected among the subscribers with packets in the queue in step 620. The three conditions are $N_{sel} = 0$ (step 618), not all N_{sel} subscribers in the selected combination have data in the queue (step 619), or the selected combination was determined T_{sel} ago (step 621). The parameters N_{sel} and θ_{min} are preferably set in step 622 as follows: $N_{sel} = 120/B$, $\theta_{min} = B$, where $B > 0$.

Once N_{sel} and θ_{min} are determined, all combinations of the N_{max} candidate subscribers taken N_{sel} at a time are preferably considered in step 624 to determine valid combinations of subscribers which may be served in the current hop interval according to this embodiment of the invention. For example, combinations which correspond to a minimum angular separation among subscribers of less than θ_{min} may be discarded as invalid. At step 626 a determination is made as to whether valid combinations of subscribers have been identified. If no valid combinations of subscribers are identified, N_{sel} is preferably decremented by one in step 628, and the search for valid combinations is repeated in step 624 with the new value of N_{sel}. The process of decrementing N_{sel} by one and searching for a valid combination preferably continues until either $N_{sel} = 1$ or a valid combination is found in step 626.

At step 630, beams for each N_{sel} subscriber unit in $COMB_{sel}$ are preferably formed for simultaneous service in the current hop interval. Preferably, each simultaneous beam is allocated equal transmit power.

At step 632 data rates for the subscriber units to be served in the current hop interval are preferably selected. For example, for each subscriber $k=1,2,\ldots,N_{sel}$ to be served simultaneously in the current hop interval, the C/I ratio measured on the traffic channel may be used to select the data rate from a table of required C/I ratios and corresponding data rates for the HDR system. It should be appreciated that the selection of data rates as described above uses instantaneous estimates of the C/I ratio measured on the traffic channel which may not always be available. Accordingly, a different channel measurement may be utilized to estimate the C/I ratio of the traffic channel. For example, an initial data rate for each subscriber can be chosen using the C/I ratio measured on the pilot channel and, thereafter, the data rate may be adapted as estimates of the C/I ratio measured on the traffic channel become available.

Steps 634-646 identify the subscriber units of the N_{sel} subscriber units for which the identified data rate is greater than zero (or possibly some other threshold data rate value) and provides data transmission thereto using hopping techniques as described herein. Specifically, at step 634 it is determined if the subscriber unit under consideration (k) is <= N_{sel} and, if so, processing proceeds to step 638. At step 638 it is determined if the data rate for the subscriber unit under consideration is greater than zero and, if so, processing proceeds to step 640 for adding the subscriber unit under consideration to an active list of subscriber units for transmission in the current hop interval and incrementing k to the next subscriber unit of N_{sel}. If, however, the data rate for the data rate for the subscriber unit under consideration is zero at step 638, processing proceeds to step 642 where it is determined if the data rate has been zero for this subscriber unit for a consecutive number of times greater than N_{drop}. If the data rate for this subscriber unit has been zero for N_{drop} consecutive times, the subscriber unit is preferably dropped from the system and k is incremented to the next subscriber unit of N_{sel} at step 644. If, however, the data rate for this subscriber unit has not been zero for N_{drop} consecutive times, k is incremented to the next subscriber unit of N_{sel} at step 646. When, at step 634, it is determined that the subscriber unit under consideration (k) is no longer <= N_{sel}, transmission to all subscriber units placed on the active list of subscribers

for transmission in the current hop interval is provided using hopping techniques as described herein (step 636).

Preferably, in the next hop interval, a new set of N_{max} candidate subscribers is selected as described above if any of the following conditions is satisfied: (a) there are subscribers with packet queue times greater than or equal to T_{max} in step 614; (b) the previous combination, $COMB_{sel}$, was selected less than a threshold T_{sel} ago in step 621, or; (c) not all N_{sel} subscribers of $COMB_{sel}$ have data present in the transmit queue in step 618. If none of the conditions (a), (b), or (c) are satisfied, the combination, $COMB_{sel}$, of subscribers is preferably used in the next hop interval in step 630. The N_{sel} subscribers of $COMB_{sel}$ are preferably served simultaneously in subsequent hop intervals until either condition (a) or (b) is satisfied. Typical parameters for the slow hopping algorithm are again given in Table 1.

The above algorithms may be used to determine which simultaneous beams can be utilized during a given transmission cycle, and the optimum beams to use based on subscriber location, signal strength, and the other parameters described above. When combined with frequency and/or time-slot hopping, significant increases in system capacity may be realized as shown below.

<center>SIMULATION RESULTS</center>

The simulation described below confirms the efficacy of the fast and slow-hopping algorithms disclosed above.

<center>Analysis of Throughput and Coverage Increases</center>

Aggregate forward link throughput is evaluated for a HDR system with hexagonal geometry, reuse factor one, and typical system parameters as shown in Table 1. Stationary subscribers are placed uniformly within a 120° sector of a central cell. Interference from the six first tier cells is considered. The propagation model consists of path loss of the form d^{-n} and lognormal shadowing with standard deviation σ dB. Packet requests are generated according to a Poisson process with the rate of requests proportional to the C/I of each subscriber. Packets with queuing time greater than a threshold T_{max} receive top priority for

transmission. A service attempt fails if the C/I of a subscriber selected for service is less than the minimum C/I required for transmission. A subscriber is dropped from the system if the number of consecutive failed service attempts exceeds a drop threshold N_{drop}. The coverage is defined as the percentage of subscribers that are not dropped from the system. The

5   throughput and coverage are compared for a system with fast hopping, slow hopping and no beam forming.

Table 2 summarizes the throughput and coverage results for the three systems under consideration.

Table 2: Simulation Results

	Throughput (kbps)	Coverage (%)
No Beam Forming	330	82
Fast Hopping	1100	94
Slow Hopping	1300	94

The simulation results indicate that space-time hopping can provide more than three times the throughput and increase coverage when compared to a system without beam forming. It is envisioned that space-frequency and space-time-frequency hopping will similarly provide capacity improvement.

Analysis of Interference Diversity Gain

The gain due to interference diversity is analyzed for fast hopping for the cases of single and multiple interferers.

20   Interference Diversity Gain: Single Interferer

A serving base station and interfering base station with 120° sectors are considered. Stationary subscribers are served using fast hopping with beams of width B°. The probability that a subscriber is illuminated by an interfering beam is given by $p = B/120$. Therefore, the interference, I, seen by a subscriber can be modeled by the following distribution:

25          $\Pr(I = 0) = 1\text{-}p;$ $\Pr(I = I_0/p) = p.$

The mean interference power is $E(I) = I_0$. The received signal power is represented by S, and thermal noise variance is σ^2. Two quantities of interest, the signal-to-interference-plus-noise ratio (SINR) and the interference-to-noise ratio (INR), are defined by

$$SINR = S/(I_0 + \sigma^2)$$

5              $$INR = I_0/\sigma^2.$$

The coded bit error rate (BER) performance of a system using fast hopping is compared to that of a system without beam forming. The mean interference power for both systems is I_0. Errors in adjacent bits are assumed to be independent after de-interleaving. A rate ¼ convolutional code (with generator matrix [765 671 513 473]) is applied to the de-interleaved bit stream. The coded BER for both systems with $p = 0.25$ ($B = 30°$) and INR = 10 dB is plotted in FIGURE 7.

From FIGURE 7, the diversity gain of fast hopping with a single interferer is approximately 7.5 dB (at 10^{-2} coded BER).

Interference Diversity Gain: Multiple Interferers

The interference diversity gain for a cellular system with hexagonal geometry is evaluated. A reuse factor of one is used, and the interference from the six first tier cells is considered. A path loss of the form d^{-n} is assumed, where d is the distance between a subscriber and a base station and n is the path loss exponent. A probability distribution of the mean interference power (averaged over lognormal shadowing) seen by a given subscriber is obtained from the path loss and the probability of illumination, p, by an interferer. For a given subscriber position, the interference diversity gain for fast hopping is computed as previously described. The interference diversity gain is then averaged over all subscriber positions within a cell. The average interference diversity gain is plotted in FIGURE 4 for different beam widths B.

It should be appreciated that, although preferred embodiments have been described herein with reference to the forward link, the concepts of the present invention may be

applied to reverse link communications as well. For example, one of ordinary skill in the art will appreciate that the hopping techniques and identification of multiple subscribers to provide simultaneous communications in a particular hop interval of the present invention may be used in the reverse link.

5   Although the present invention and its advantages have been described in detail, it should be understood that various changes, substitutions and alterations can be made herein without departing from the spirit and scope of the invention as defined by the appended claims. Moreover, the scope of the present application is not intended to be limited to the particular embodiments of the process, machine, manufacture, composition of matter, means,

10   methods and steps described in the specification. As one of ordinary skill in the art will readily appreciate from the disclosure of the present invention, processes, machines, manufacture, compositions of matter, means, methods, or steps, presently existing or later to be developed that perform substantially the same function or achieve substantially the same result as the corresponding embodiments described herein may be utilized according to the

15   present invention. Accordingly, the appended claims are intended to include within their scope such processes, machines, manufacture, compositions of matter, means, methods, or steps.